A New Way to Locate Corotation Resonances in Spiral Galaxies

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ABSTRACT

Kinematical information over the entire disk of a spiral galaxy can be used in a new way to locate the position of the corotation resonance. The spiral residual velocity field has a global appearance that is distinctly different inside and outside the corotation resonance radius. Inside the corotation radius, the spiral velocity field shows a single spiral feature (that is, a single approaching-receding "spiral arm" pair). Outside the corotation radius, there are three spiral features (approaching-receding arm pairs). The corotation radius is located where this morphological change occurs. The effect is a consequence of geometric phase. It should apply generally, regardless of the functional form of the velocity perturbation due to a spiral arm, if the spiral structure is wave-based.

Subject headings: Galaxies: Internal Motions — Galaxies: Structure

1. Introduction

Despite attempts to determine the pattern speed of spiral structure in many galaxies, it has not been conclusively measured in any grand design spiral galaxy. As an example, consider corotation resonance radius measurements for the nearby and well-studied M81. (Determining the pattern speed and locating the corotation resonance radius are identical tasks.) Visser (1980) modeled the velocity field, finding a corotation resonance radius $R_{\rm cr} = 11.3\,{\rm kpc}$. In detailed kinematic analyses, Sakhibov & Smirnov (1989) derived $R_{\rm cr} = 11\,{\rm kpc}$, nearly the value deduced by Visser. Elmegreen, Elmegreen, & Seiden (1989) and Elmegreen, Elmegreen, & Montenegro (1992) used symmetries of spiral features to locate resonances. In their purely photometric study, they deduced $R_{\rm cr} = 7.2\,{\rm kpc}$. Westpfahl (1991), using a technique described by Tremaine & Weinberg (1984) that uses the continuity equation, deduced $\mathrm{R}_{\rm cr} = 9.3\,{\rm kpc}$.

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There clearly are observational conflicts in the measurement of pattern speeds. It is vital now to have a simple way to check the multiplying predictions of corotation resonance radii. Until at least one clear pattern speed measurement is made, reliable and detailed modeling cannot proceed. A new technique presented in this paper can help to alleviate the observational bottleneck. Kinematical information is used to reveal a fundamental change in the morphology of the spiral velocity field that happens at corotation, if the spiral structure is wave-based.

2. Presentation

A model of an observed velocity field for an inclined, two-armed spiral galaxy is shown in Figure 1. The model galaxy is inclined 35° to the plane of the sky, and the pitch angle of the spiral arms is 10°. The velocities were computed from analytic transsonic (§3.2) solutions to equations describing the motion of gas in a model spiral galaxy (Shu et al.1973; Visser 1980). The rotation curve of the model galaxy is flat, so isovelocity contours unperturbed by spiral structure would be straight lines. Wiggles in the isovelocity contours are due to motions caused by the spiral structure. [A similar figure modeling a specific galaxy (M81) may be seen in Visser (1980), Fig. 10]

Figure 2 shows the line-of-sight radial velocity field due only to the spiral density wave in the same two-armed spiral galaxy model as in Fig. 1. The velocities in Fig. 2 are *what an observer would measure* after subtracting the axisymmetric velocity field. That is, the axisymmetric (rotation curve) part of the velocity field has been omitted from Fig. 2.

The corotation circle marks the boundary between two regions of very different morphology. Inside corotation, there is one spiral (or, saying it differently, one approaching-receding pair of spiral arms) in the residual velocity field. It winds in the same sense as the spiral arms. Outside corotation, there are three spirals (that is, three approaching-receding spiral arm pairs), also winding in the same sense as the spiral arms. This effect will be explained in two different ways in §3. Its basis is fundamental. It does not rely on the exact functional form for the spiral velocity perturbations.

3. Justification

3.1. Geometric Phase

The new technique for locating the corotation resonance relies on what will be referred to as the "geometric phase" effect. Common manifestations of geometric phase include such diverse effects as the one day difference between the siderial and solar year and the twisting of a garden hose when it is picked up off the ground and wrapped around a spool.

The sometimes surprising consequences of geometric phase can be seen in a counterintuitive trick involving two coins. Take two of the same coin, preferably with a ridged edge. Hold one coin stationary on a flat surface and allow the second coin to roll without slipping around the periphery of the first coin. How many times will the head of the figure of the rolling coin appear to rotate when it completes one circuit of the stationary coin?

Although the circumferences map one-to-one, the head of the figure will have rotated *twice*. In addition to the 2π radians of phase acquired by the rolling coin owing to the coins' identical circumferences, there is an additional geometrical phase (of 2π radians) due to the completion of a circuit about the stationary coin. Note that the sense of rotation of the rolling coin is the same as the sense of advancing phase of the circuit around the stationary coin.

The lesson of the above example may be applied to spiral velocity perturbations. For a two-armed spiral, there are 4π radians of phase in a complete circuit of the disk. (For an m-armed spiral, there are $2m\pi$.) The analogous "coin puzzle" involves a stationary coin with twice the diameter of the rolling coin. The figure on the rolling coin will rotate $2+1 = 3$ times in one circuit of the stationary coin. This corresponds to the spiral velocity field behavior outside corotation (Fig. 2). If the rotation direction of the rolling coin were opposite that of the direction of its circuit, then the figure on the rolling coin would rotate $2 - 1 = 1$ time in its circuit. This would correspond to the spiral velocity field inside corotation (Fig. 2).

Consider gas flow in a spiral galaxy. The radial flow direction inside the corotation circle is opposite that outside corotation, while the azimuthal flow direction is unchanged. Figure 3 shows a typical relationship between the gas velocities perpendicular to the spiral arm ($u_{\eta 1}$) and parallel to the arm ($u_{\xi 1}$) for illustrative purposes only. Inside corotation, for a constant radius but with advancing spiral phase, the velocities traverse the path (Fig. 3) in a counter-clockwise direction. The shock is a decelerative one: gas catches up with the slower-moving spiral pattern. Outside corotation, the pattern moves faster than the material, entraining it. The shock is an *accelerative* one. There, velocities traverse the path in a clockwise direction with advancing spiral phase. This change in "circulation" direction between inside and outside corotation, coupled with the effects of geometric phase, causes the difference in global morphology seen in Fig. 2.

The effect is not confined to two-armed spirals. Inside the corotation circle, the residual velocity field will have one fewer approaching-receding arm pair than the number of (photometric) spiral arms. Likewise, the spiral velocity field outside corotation will have one additional approaching-receding arm pair.

3.2. Trigonometry

The following analysis uses the functional form for transsonic solutions to the differential equations describing the flow of a single-component, cold, nonviscous fluid in a disk with an imposed spiral potential (Shu et al.1973). These solutions are used for illustrative purposes only. The change in global morphology illustrated in Fig. 2 occurs if the spiral structure is wave-based. One consequence of this condition is that the component of the velocity perturbation perpendicular to the arm changes sign across the corotation resonance, but the sign of the parallel component does not. This behavior corresponds to the well known 90° phase shift of the major axis of an epicyclic orbit across a Lindblad or corotation resonance (Contopoulos & Papayannopoulos 1980). In Fig. 1, the spiral velocity perturbations on the major axis (showing mostly the parallel component of the perturbations) are in the same direction both inside and outside corotation. The spiral velocity perturbations have opposite signs inside and outside corotation in Fig. 1 on the minor axis (showing mostly the perpendicular component of the velocity perturbations).

The functions describing the velocity perturbation are

$$u_{\xi 1} = A \sin \eta \tag{1}$$

$$u_{\eta 1} = \nu B \cos \eta, \tag{2}$$

where η is the spiral phase (range 0 to 4π in a two-armed spiral). $u_{\eta 1}$ is the spiral radial component and $u_{\xi 1}$ is the spiral azimuthal component. $\nu = (\Omega_p - \Omega)/\kappa$ is the normalized radial coordinate in standard notation. ν changes sign across the corotation resonance, so $u_{\eta 1}$ changes sign there while $u_{\xi 1}$ does not. A and B are radial functions that are non-negative between Lindblad resonances: $A = \kappa^2 R f(\sin\alpha)/2m\Omega(1-\nu^2+x)$, and $B = \kappa R f(\sin\alpha)/m(1-\nu^2+x)$. (See Shu et al.) α is the pitch angle. Generally, $A \approx B$; for a flat rotation curve, $\sqrt{2}A = B$.

The radial and tangential components of the spiral velocity field in the plane of the disk are

$$u_r = \nu B \cos \eta \cos \alpha - A \sin \eta \sin \alpha, \tag{3}$$

$$u_\theta = \nu B \cos\eta \sin\alpha + A \sin\eta \cos\alpha. \tag{4}$$

Let the $\eta = 0$ ray be the line of nodes, for convenience; let θ be the angle from the line of nodes in the plane of the disk. The line-of-sight radial velocity in an inclined disk is

$$V_{\rm obs} = [\nu B \cos 2\theta \sin(\theta + \alpha) + A \sin 2\theta \cos(\theta + \alpha)] \sin i. \tag{5}$$

Inside the corotation resonance, $A \approx B$ implies

$$V_{\rm obs} \sim A \sin(\theta - \alpha) \sin i. \tag{6}$$

The periodic dependence on θ leads to a single approaching-receding spiral arm pair inside corotation.

Outside corotation,

$$V_{\rm obs} \sim A \sin(3\theta + \alpha) \sin i. \tag{7}$$

The dependence on 3θ leads to three spiral arms in the velocity residuals outside corotation. Sakhibov & Smirnov (1989) also derived the 3θ term, although they did not indicate its dominance.

Spiral velocity perturbations in a real galaxy are probably not sinusoidal (Roberts & Stewart 1987), complicating the above analysis. This complication does not change the conclusion, since the geometric arguments of §3.1 still apply. Skewed sinusoidal (but periodic) velocity perturbation functions $u_{\eta 1}$ and $u_{\xi 1}$ lead to noncircular (but convex) graphs like Fig. 3. Such skewness leads to one arm of uneven width in the velocity residuals inside corotation and three unequally spaced arms outside corotation; but the change in morphology from one to three arms persists nonetheless.

4. Application

To use the geometric phase technique, identify and subtract the axisymmetric part of the velocity field to reveal the symmetry of the spiral residuals and thereby deduce the corotation resonance radius. Observations of regular, two-armed spiral structure in flat disks should yield clear results. To observe the largest effect, seek faster rotating galaxies or those with more open spiral arms.

If spiral arms are not wave-based, but rather are material arms, then the overdensity of the arm will always pull the material in the same direction. In this case, the geometric phase method will show no morphological change related to the corotation resonance.

Wave-based theories of spiral structure [modal theory (e.g., Bertin et al. 1989), swing amplified arms (e.g., Toomre 1981), and groove modes (Sellwood & Kahn 1991)] all predict the same *direction* for velocity perturbations due to the spiral structure. The geometric phase method, which is based on the mere morphology of approaching and receding velocities, cannot distinguish these theories. Detection of three-armed spiral-form velocity residuals, though, would confirm that the spiral structure in a galaxy was produced by a wave-based phenomenon. The location of the corotation resonance for the spiral structure is, however, a matter of some contention among wave-based theories [see Contopoulos & Grosbøl (1986, 1988) for a view counter to that expressed in the three previous references]. The relative location in the disk of the corotation resonance could be used as evidence for or against the operation of some of the wave-based theories. For example, detection of three-armed velocity residuals in a given galaxy would rule out (for that particular galaxy) the contention by Contopoulos & Grosbøl that strong spiral structure ends at the inner 4:1 resonance.

The geometric phase method can be applied to barred and ringed galaxies. The hypothesis that rings or pseudorings form at the Lindblad resonances (Schwarz 1981; Buta 1988 and references) can be tested. If bars end near their corotation resonances (Contopoulos 1980; Binney & Tremaine 1987), then measurement of the spiral pattern speed in a barred galaxy will test the assertion by Sellwood & Sparke (1988) that bars and spiral patterns need not have the same pattern speeds. If the bar and the spiral have the same pattern speed, then there should be three spirals in the velocity residuals because the entire spiral pattern would be beyond its corotation radius (the bar end). If outer rings are at outer Lindblad resonances, then three spirals should appear in the velocity residuals interior to the outer ring.

If the rotation curve is not symmetrical, then determining the axisymmetric part of the velocity field will be problematic. The velocity field to be subtracted should not be constructed from a rotation curve that has bumps and wiggles due to motions associated with the spiral structure. Otherwise, the very effects we try to measure will have been removed or distorted by the inappropriate subtraction. Using tilted ring models (Bosma 1981) may also fit out the velocity perturbations of the spiral density wave. The axisymmetric and spiral parts of the the velocity field should be fitted simultaneously (Sakhibov & Smirnov 1987, 1989).

The published maps of residual velocities have nearly always appeared almost random (e.g., NGC 4258: van Albada 1980; NGC 3198: Bosma 1981; NGC 2903, 5033, and 5371: Begeman 1987). If, however, spiral density waves are mostly responsible for the spiral structure in these galaxies, and if the motions due to the spiral density waves are large enough to be detectable, then velocity residuals should be correlated and should have spiral form. The fact that regular patterns have not usually been seen suggests that the spiral component of the observed velocities has been removed by the fitting. Otherwise, the absence of regular, correlated residuals would imply that spiral density wave theories are incorrect.

The residuals left after subtracting Visser's (1980) best model axisymmetric velocity field from the observed velocity field of M81 (Figure 4) clearly show a single-armed spiral to 8.5 kpc radius. This part of the disk, then, is inside its corotation radius. Fig. 4 was constructed graphically from Visser's measured velocity field (his Fig. 4) and Visser's axisymmetric model velocity field (his Fig. 10a). Wiggles protruding to either side of the axisymmetric isovelocity contour were shaded according to whether they were at a relatively greater or lesser velocity. This procedure graphically subtracts the axisymmetric velocity field, leaving a shaded map of residuals owing only to the spiral structure. Applying the same procedure to Fig. 1 will show the same one-armed and three-armed spiral pattern of the velocity residuals depicted in Fig. 2.

H I observations of M101 (Bosma, Goss, & Allen 1981) provide a less convincing example of spiral-form velocity residuals, but it is the only explicit case in the literature. In M101, there is one approaching-receding spiral pair over nearly the entire optical disk, implying a two-armed photometric spiral; but M101 does not appear to be so morphologically simple. (However, see Block & Wainscoat 1991. Also, the reliability of this example is weakened by the small inclination of M101.)

Warped disks, close companions, and tidal flows resulting from interactions may all distort the velocity field and prohibit application of the geometric phase method. For those reasons, the following galaxies are probably not good targets:

NGC 1097 (cf. Ondrechen, van der Hulst, & Hummel 1989) does not have a symmetrical rotation curve. This fact is attributable to its companion (NGC 1097A).

NGC 4731 (cf. Gottesman et al.1984) has a bar, very open spiral structure, and a nearby dwarf companion (RNGC 4731A: Erickson, Gottesman, & Hunter 1987). There is a large velocity spread about the mean rotation velocity at a given radius. Deprojection makes the arms look strange, suggesting an interaction with RNGC 4731A.

NGC 5371 (cf. Wevers, van der Kruit, & Allen 1988; Begeman 1987) is probably three-armed, not two-armed. Its H I emission is knotty and concentrated in a fat outer ring near the edge of the optical disk. It is near the group containing NGC 5350, 5353, 5354, 5355, and 5358, but is separate from them on the sky.

Of the galaxies that have been observed interferometrically in H I emission (Huchtmeier & Richter 1989), the following are good candidates for application of the geometric phase method to high resolution observations:

NGC 1365 (cf. Ondrechen & van der Hulst 1989) is barred and has very open spiral structure. There may not be sufficient interarm H I gas to be detectable, which could make it difficult to identify the one- or three-armed spiral pattern in the velocity residuals.

NGC 2903 (cf. Wevers et al.1988; Marcelin, Boulesteix, & Georgelin 1983) has two main spiral arms, but there appear to be two shorter ones just outside the main arms. It is a field galaxy and its rotation curve is symmetrical. It has a small bar immersed in a flocculent inner disk. The spiral arms do not emerge from the bar ends. Using a global fit to the velocity field, Sakhibov & Smirnov (1989) deduced a spiral pattern speed that places corotation well within the optical disk.

NGC 3359 (cf. Ball 1986) is barred; it has two asymmetrical optical spiral arms, but the H I arms are symmetrical. The H I arms extend well beyond the optical disk, and H I emission covers most of the disk as well. Although there is a faint, dwarf companion, the disk of NGC 3359 is not warped. Its rotation curve rises to slightly higher velocities in the northern half.

NGC 4535 (cf. Cayatte et al.1990; Guhathakurta et al.1988) is at the outskirts of the Virgo cluster. Its two-armed photometric spiral pattern is very clear in the inner disk, but the pattern breaks up into a multi-armed structure in the outer disk. H I emission covers most of the disk. Its rotation curve is symmetrical.

NGC 4548 (cf. Warmels 1988; Cayatte et al.) is barred; inner spiral arms extend beyond the bar ends. It has a central lens and a "theta" appearance optically and in H I emission. This galaxy also resides in the Virgo cluster. H I emission does not extend far beyond the optical disk. There is no evidence of interaction with other galaxies.

NGC 5383 (cf. Sancisi, Allen, & Sullivan 1979) is strongly barred. Its two spiral arms overshoot the bar, forming an inner pseudoring. The outer H I velocity field is regular and the rotation curve is symmetrical. There is a dwarf barred spiral companion (UGC 8877) three arcminutes ($21h^{-1}$ kpc projected) to its south and within $120\,\mathrm{km\,s^{-1}}$ of its redshift. Warping of the outer disk by the companion is unlikely.

The following candidates are less promising because of potential difficulties, but should not be ignored outright:

NGC 1300 (cf. England 1989b) is barred and has two prominent spiral arms. The H I emission follows the optical arms, then extends well past the optical disk and fills most of the area, but is knotty. Its apparently asymmetrical rotation curve (England 1989a) may be an artifact of the choice of kinematic parameters.

NGC 3992 (cf. Gottesman et al.1984) is barred and may have four arms. If it does have four arms, then the residual spiral velocity field should have three arms (§3.1). The three-armed pattern of velocity residuals presented by Hunter et al.(1988, their Fig. 12) probably indicates the lack of success that their models have in reproducing the spiral structure of NGC 3992. The pattern of their Fig. 12 probably is not related to the geometric phase method. That is because Fig. 12 in Hunter et al.is the difference between the full model velocity field and the full observed velocity field, and so would be random if the modeling were successful. Hunter et al.claim that the bar significantly influences the velocity field outside it; perhaps the influence of the bar has led to the correlated residuals in their Fig. 12. Alternatively, perhaps the spiral velocities in their model are small compared to the actual spiral velocities. In that case, subtraction of the model velocity field would leave the spiral velocity field mostly intact, but would also remove the parts of the velocity field owing to nonspiral components (bar, disk, halo). Fig. 12 of Hunter et al.would then be a nearly proper application of the geometric phase method, and the three-spiral pattern it showed would indicate spiral structure outside its corotation resonance.

NGC 4258 has three companions (NGC 4248, UGC 7335, and UGC 7356: Rubin & Graham 1990; Erickson et al.1987). Its pair of Hα and radio continuum "anomalous arms" (van Albada & van der Hulst 1982) look like very open spiral arms. They are probably not spiral density waves, and do not perturb the H I velocities (van Albada 1980). There is a small bar-like structure in H I emission at its center.

NGC 4321 (cf. Cayatte et al.), a Virgo cluster member, is clearly two-armed. Two dwarf elliptical galaxies (NGC 4322 and 4328) appear nearby, but only NGC 4322 appears to be physically associated with NGC 4321, being linked by a faint bridge. The rotation curve is not symmetrical beyond three arcminutes radius (Guhathakurta et al.).

NGC 5905 (cf. van Moorsel 1982) has two prominent spiral arms, but interarm arcs as well. It forms a pair with the S0 galaxy NGC 5908.

Many of the most promising pure spiral galaxies have not been observed interferometrically. These include NGC 0210, 1566, 4536, 5247, and 5364. The galaxies NGC 2713, 2997, 3513, and 5248 may also be worthy targets. Beware: some are members of loose groups (NGC 1566, 5364); others are paired with another bright galaxy (NGC 2713, 3513, 4536), and one has a faint companion (NGC 210).

There is in the literature one clear case (M81) and one marginal case (M101) of spiral-form velocity residuals. These cases suggest that wave-based theories of spiral structure have merit. However, wave-based theories also rely on amplification of the waves at the corotation resonance. Wave-based theories would be threatened if kinematic analyses (using the geometric phase method, for example) did not find corotation within the H I disk. That is because it would be hard to believe that enough action could be produced beyond the edge of the H I disk to provide the necessary amplification. Alternatively, unambiguously locating the corotation resonance in even one spiral galaxy would provide the key modeling parameter that to date has only been guessed. Either outcome would be interesting.

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FIGURE CAPTIONS

Fig. 1.— This is a model velocity field (line-of-sight observed velocities) of a two-armed spiral galaxy. The model galaxy disk is inclined 35° to the plane of the sky, and the spiral arms have pitch angle 10°. The rotation curve is flat (at $300\,\mathrm{km\,s^{-1}}$) and the spiral potential is 15% of the axisymmetric potential. Contours (bold) are separated by $20\,\mathrm{km\,s^{-1}}$. The thinner, straight lines are the unperturbed (axisymmetric) velocity contours by which the spiral perturbations may be gauged. The minima of the two-armed spiral potential are graphed as dashed curves.

Fig. 2.— This is a model velocity field due solely to a spiral density wave. That is, the axisymmetric component of the motion has been removed. The line-of-sight radial velocities are represented by lighter shades for approaching velocities and darker shades for receding. The model galaxy is the same one as in Fig 1. The inner and outer Lindblad resonances bound the inner and outer edges of the elliptical annulus, and the corotation resonance is shown as an ellipse. The minima of the two-armed spiral potential are graphed as dashed curves.

Fig. 3.— Diagram showing typical qualitative relationship between velocities due to the spiral density wave, showing components parallel to ($u_{\xi 1}$) and perpendicular to ($u_{\eta 1}$) spiral arms.

Fig. 4.— This is the result of applying the geometric phase method to Visser's H I observations of M81. The smooth isovelocity contours drawn as fine lines are Visser's axisymmetric model velocity field. The wiggly, bold curves are the observed velocities. Parts of the observed velocity field that protrude from the axisymmetric contours to higher velocity have been shaded darker than those that protrude in the other direction. This procedure graphically subtracts the axisymmetric velocity field, leaving velocity residuals due only to the spiral structure. A single light-dark spiral pair is clear, implying that all of the shaded spiral structure is inside its corotation resonance. The single pair will become three oppositely-shaded pairs outside corotation.